

Article

Characteristics and Contributing Factors to Low-Visibility Weather at Lhasa Airport

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Abstract

Low-visibility weather poses a significant threat to aviation safety and operational efficiency. Lhasa Airport is situated in a high-altitude river valley region prone to dust events. Clarifying the characteristics and dominant factors of low-visibility weather is crucial for enhancing aviation meteorological support capabilities. This study systematically analyzed the weather types, spatiotemporal distribution characteristics, and key meteorological influencing factors of low-visibility events using ground-based automated meteorological observation data, monthly summary records, and wind lidar data from Lhasa Airport from January 2020 to July 2024. The results indicate that dust weather (blowing sand and floating dust) is the primary cause of low visibility, accounting for over 90% of low-visibility days. Low-visibility events exhibit significant monthly variations, with the longest cumulative duration occurring in January and February, while being extremely rare from July to November. Under low-visibility conditions, visibility levels are predominantly concentrated in the 3–4 km range (72.5%), and most events last less than one hour. Factor analysis reveals that north, easterly, and west winds are commonly associated with dust-induced low visibility. Wind speed demonstrates a significant negative correlation with visibility and serves as the primary driving factor. Moderate relative humidity is most conducive to maintaining visibility between 3 and 5 km. Case studies further confirm that sustained strong low-level winds (≥ 10 m/s), high surface wind speeds (≥ 7.5 m/s), and intense upward motion are the key dynamic conditions for triggering and maintaining dust-related low-visibility processes. This study presents, for the first time, quantitative thresholds for key meteorological parameters and their season-dependent characteristics for dust-induced low-visibility events at Lhasa Airport, and proposes actionable forecasting indicators. These findings offer clear practical implications for aviation meteorological services at high-altitude valley airports.

Keywords: low visibility; dust weather; Lhasa Airport; spatiotemporal distribution; meteorological drivers



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1. Introduction

Low-visibility weather poses a serious challenge to aviation safety and operational efficiency. According to the operational standards of Lhasa Airport, low-visibility procedures must be initiated when visibility or runway visual range falls below 5 km. Such weather conditions significantly increase the risks of flight delays, cancellations, and even incidents [1,2]. Consequently, accurately understanding and forecasting low-visibility weather is crucial for ensuring safe and efficient flight operations at high-altitude airports.

Research on visibility encompasses various aspects, including observation methods, numerical modeling, physical mechanisms, and variation characteristics. Manual and instrumental observations are the two primary approaches [3,4], with the latter generally providing more objective and higher-resolution data within the 0–10 km range [5]. Regional studies have shown that visibility variations are driven by multiple contributing factors, such as wind speed [6–8], temperature [9], relative humidity [10–12], particulate matter concentration [13,14], and precipitation [15]. For instance, in the Urumqi urban area, wind speed has been identified as the dominant meteorological factor influencing visibility [16].

In the Tibetan Plateau region, dust events have been recognized as a primary meteorological hazard causing low visibility and affecting flight take-offs and landings at airports [17]. Previous climatological studies have revealed the spatiotemporal distribution characteristics of dust events on the plateau and their association with large-scale circulations like the westerly jet stream, noting a decreasing trend in their activity linked to vegetation changes and weakening of the westerly jet [18–20]. In recent years, with the advancement of observation technologies, lidar has demonstrated unique advantages in capturing the vertical structure and transport processes of dust aerosols [21]. Meanwhile, machine learning methods have been increasingly applied to the statistical forecasting of visibility and dust weather [4]. However, existing research has largely focused on macro-climatological analyses, lacking systematic, high-spatiotemporal-resolution studies on low-visibility weather at specific plateau aviation hubs, such as Lhasa Airport.

Specifically, for Lhasa Airport, the fine-scale spatiotemporal distribution patterns of dust-dominated low-visibility events, their quantitative relationships with key meteorological parameters (e.g., wind field structure, temperature, humidity), and the specific dynamic mechanisms governing the initiation and development of such events remain insufficiently elucidated. This knowledge gap limits the accuracy of low-visibility weather forecasting and the effectiveness of aviation meteorological services for this airport.

Therefore, this study aims to address that deficiency. We will comprehensively utilize high-resolution ground-based automatic observation data, monthly summary reports, and wind lidar data from Lhasa Airport spanning January 2020 to July 2024 to systematically analyze the statistical characteristics and key meteorological influencing factors of low-visibility weather (particularly dust-induced). This study not only aims to characterize the observed phenomena but also places greater emphasis on quantifying the thresholds of key meteorological parameters. By integrating minute-scale ground observations with wind lidar data, it reveals the fine three-dimensional dynamical structure of localized dust processes at Lhasa Airport. Furthermore, we will dissect the dynamic processes through typical case studies. The findings are expected to deepen the understanding of the formation mechanisms of low visibility at high-altitude airports, refine an analytical framework with potential generalizability, and provide a solid scientific basis for enhancing aviation weather forecasting capabilities at Lhasa Airport. And we provide a concrete quantitative basis for nowcasting and operational decision-making in aviation meteorology.

2. Materials and Methods

2.1. Materials

This study aims to reveal the association between low-visibility weather and various weather phenomena at Lhasa Airport and to analyze the key meteorological drivers of visibility under the influence of dust events. To more accurately analyze visibility variation characteristics and align closely with manual observation results, this study uses Meteorological Optical Range (MOR) as the visibility metric instead of Runway Visual Range (RVR). Although RVR is directly relevant for flight operations, MOR correlates better with manually observed prevailing visibility and is recognized by the International Civil Avia-

tion Organization (ICAO) as a valid substitute for visibility in automated meteorological observations [22]. Furthermore, RVR data can be significantly influenced by runway light intensity. Therefore, this study uniformly utilizes minute-resolution MOR observations for analysis. The data used are as follows:

Airport Automatic Weather Observing System (AWOS) data. Lhasa Airport has three AWOS stations located at both ends and the middle of the runway. This study utilized minute-resolution observations of wind speed, wind direction, precipitation, relative humidity, pressure, temperature, and MOR, along with wind speed and direction data with a 15 s resolution. The quality of all data was good, with missing rates not exceeding 2%. Since the 2024 data only covers the first seven months and cannot represent the annual distribution, it was excluded from interannual variation analysis and only used for monthly and diurnal variation analyses.

Monthly summary reports from the airport meteorological office. The data range from January 2020 to July 2024. The reports record basic observation items, such as weather phenomena, surface wind, clouds, visibility, and temperature. This study primarily used the “Weather Phenomena and Visibility Evolution” table, which includes 22 weather phenomena (e.g., rain, snow, thunderstorm, sandstorm, blowing sand) along with their start/end times and corresponding visibility evolution. By aligning the timing of weather phenomena in this table with the MOR data from AWOS on a temporal axis, the specific weather types causing low visibility were accurately identified.

Wind Lidar Data. The data came from the wind lidar at Lhasa Airport, including Plan Position Indicator (PPI) and Doppler Beam Swinging (DBS) scan mode data, used to analyze the three-dimensional wind field structure during low-visibility processes.

The monthly averages of relevant meteorological parameters are presented in Table 1.

Table 1. Monthly average values of relevant meteorological parameters at Lhasa Airport (2020–2023).

Month	Visibility (m)	Wind Speed (m/s)	Temperature (°C)	QNH (hPa)	Relative Humidity (%)
1	35,600	3.0	−0.4	1019.8	31
2	32,900	4.1	4.0	1020.1	29
3	30,800	3.8	6.1	1022.3	30
4	32,400	3.4	9.1	1024.8	38
5	32,300	4.0	13.9	1023.7	43
6	37,700	3.7	18.4	1023.1	44
7	34,100	3.0	16.3	1025.6	61
8	37,600	2.7	16.0	1027.0	62
9	38,600	2.8	14.9	1029.0	59
10	36,800	3.0	9.9	1028.0	44
11	37,800	2.8	5.3	1026.4	34
12	34,000	2.2	−1.7	1023.3	35

2.2. Methods

In this study, a low-visibility event was defined when the MOR value fell below 5 km. Based on the aligned weather phenomena and MOR data, all low-visibility samples were filtered and categorized (dust, precipitation, etc.) according to the associated weather phenomena. Statistical analyses included the following:

- Calculating the frequency of different weather phenomena and their proportion in causing low-visibility days.
- Analyzing the monthly variations (cumulative duration, number of days) and diurnal variations (occurrence/dissipation times, duration) of low-visibility events.
- Statistical analysis of the visibility level distribution during low-visibility conditions.

Analyzing the characteristics of key meteorological elements (wind direction, wind speed, temperature, relative humidity, pressure) during and at the onset of low-visibility events and their relationship with visibility, including plotting wind rose diagrams, box plots, and scatter plots and conducting correlation analysis.

Selecting two typical dust-induced low-visibility processes and using wind lidar data to analyze the evolution of low-level horizontal wind fields, vertical wind speed, and echo intensity during their initiation, maintenance, and dissipation phases to reveal the dynamic mechanisms.

3. Results

3.1. Statistics of Weather Phenomena Leading to Low Visibility

Excluding the potentially biased 2024 data for interannual statistics, the main weather phenomena that could cause low visibility from January 2020 to December 2023 were analyzed (Table 2). Blowing sand and rain were the most frequent phenomena (both 421 days), accounting for 43.6%, followed by floating dust (59 days, 6.1%), while snow and fog occurred less frequently. Table 3 summarizes the number of low-visibility days caused by these weather phenomena. The total number of low-visibility days over the four years was 127. Blowing sand was the primary cause (104 days, 81.9%), followed by floating dust (11 days, 8.7%). Combined, dust events (blowing sand and floating dust) accounted for over 90% of low-visibility days. Precipitation caused less than 10% of low-visibility days, and fog did not cause any. The annual average number of low-visibility days was 31.8, with the highest in 2023 (41 days) and the lowest in 2022 (26 days). In each year, dust events accounted for over 85% of low-visibility days. These results conclusively demonstrate that dust events are the primary cause of low visibility at Lhasa Airport.

Table 2. Occurrence days and proportion of main weather phenomena at Lhasa Airport (2020–2023).

Year	Blowing Sand (Days/Proportion)	Floating Dust (Days/Proportion)	Snow (Days/Proportion)	Rain (Days/Proportion)	Fog (Days/Proportion)	Total (Days)
2020	105/42.0%	16/6.4%	14/5.6%	115/46.0%	0/0%	250
2021	93/39.2%	23/9.7%	4/1.7%	117/49.4%	0/0%	237
2022	81/43.3%	10/5.4%	5/2.7%	88/47.1%	3/1.6%	187
2023	142/48.8%	10/3.4%	10/3.4%	101/34.7%	28/9.6%	291
Total	421/43.6%	59/6.1%	33/3.4%	421/43.6%	31/3.2%	965

Table 3. Number and proportion of low-visibility days caused by different weather phenomena (2020–2023).

Year	Blowing Sand (Days/Proportion)	Floating Dust (Days/Proportion)	Snow (Days/Proportion)	Rain (Days/Proportion)	Fog (Days/Proportion)	Total (Days)
2020	21/75.0%	2/7.1%	4/14.3%	1/3.6%	0/0.0%	28
2021	25/78.1%	3/9.4%	3/9.4%	1/3.1%	0/0.0%	32
2022	21/80.8%	4/15.4%	1/3.8%	0/0.0%	0/0.0%	26
2023	37/90.2%	2/4.9%	2/4.9%	0/0.0%	0/0.0%	41
Total	104/81.9%	11/8.7%	10/7.9%	2/1.6%	0/0.0%	127

3.2. Temporal Distribution Characteristics of Low Visibility

To reveal the fine-scale temporal evolution of low-visibility events at Lhasa Airport, a systematic analysis of the monthly and diurnal variations in low-visibility events induced by dust weather was conducted for the period from January 2020 to July 2024.

3.2.1. Monthly Variation Characteristics

The total cumulative duration of dust-induced low visibility during this period was 171 h, exhibiting a highly non-uniform monthly distribution (Figure 1). The most prominent cumulative durations were observed in January and February, reaching 38.4 and 44.3 h, respectively. From March to June and in December, the cumulative duration remained at a moderate level (between 10 and 20 h, with May at 10 h). In stark contrast, the cumulative duration from July to November was extremely short, all below 1.5 h, indicating that dust-induced low-visibility events scarcely occurred during this period.

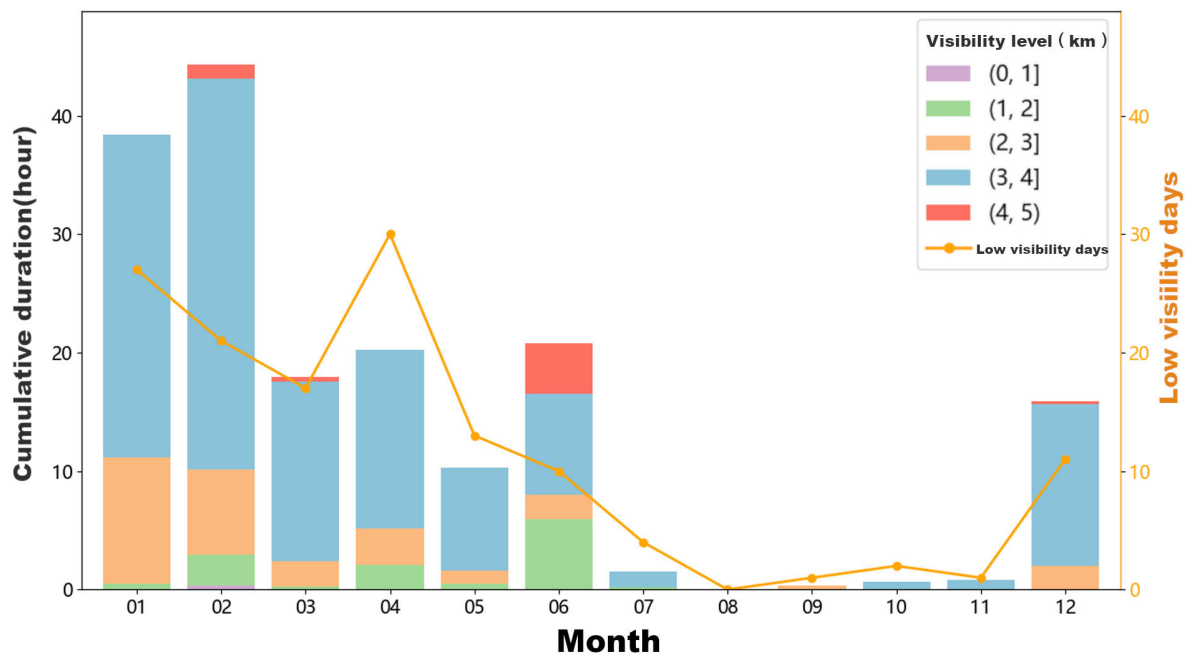


Figure 1. Monthly variation in cumulative duration (bars) and number of days (line) of dust-induced low visibility from January 2020 to July 2024.

The monthly variation trend in the number of low-visibility days showed both connections and differences compared to the cumulative duration (Figure 1). From January to March, the number of days gradually decreased from 27 to 17. A notable peak appeared in April, with the number of low-visibility days reaching 30, the maximum within the study period. It is noteworthy that although April had the highest number of days, its cumulative duration did not show a synchronous peak, suggesting that low-visibility events in this month were characterized by a high frequency but a short individual duration. The number of days plummeted to 13 in May and continued to decline thereafter, with no low-visibility days recorded in August. From September to November, the number of days remained at a very low level (≤ 2 days), and recovered to 11 days in December.

3.2.2. Visibility Level and Duration Distribution

Analysis of visibility levels during low-visibility conditions revealed that the 3–4 km level was overwhelmingly dominant, accounting for 72.5%. This was followed by the 2–3 km level (16.7%). The proportions for the 4–5 km and 1–2 km levels were both below 7%, while visibility below 1 km was the rarest, accounting for only 0.3%. In terms of event duration (Figure 2), the vast majority (75.5%, 108 events) of dust-induced low-visibility episodes lasted less than one hour. Ninety-five percent of events ended within 3 h, and less than 2% persisted for more than 6 h.

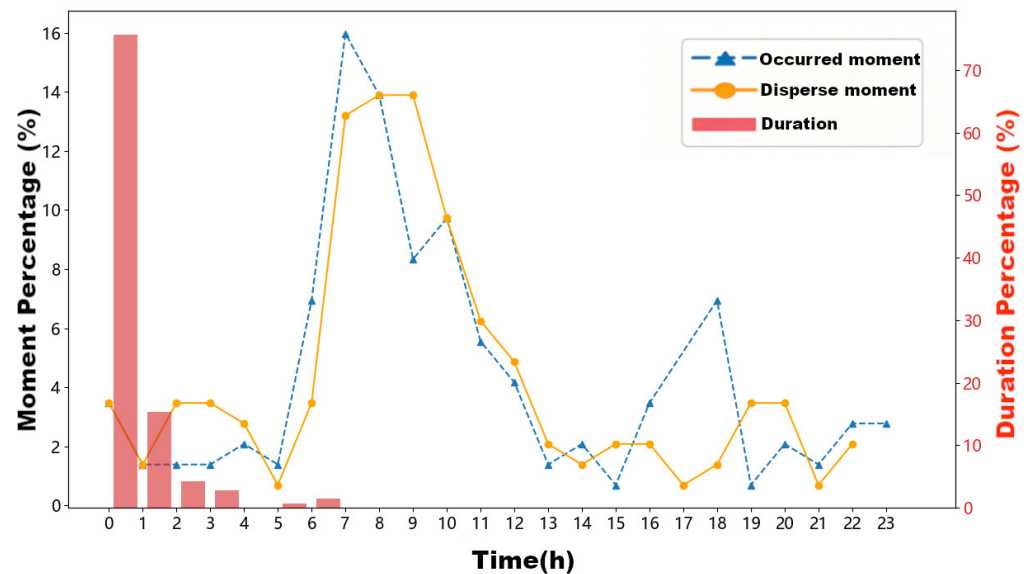


Figure 2. Distribution of occurrence frequency (blue dashed line), dissipation frequency (orange solid line), and duration (bars) of dust-induced low visibility from January 2020 to July 2024.

3.2.3. Diurnal Variation Characteristics

The occurrence frequency of low-visibility events exhibited a significant bimodal diurnal variation pattern (Figure 2). The primary peak occurred in the morning from 06:00 to 12:00, accounting for 44.9% of all events, with the peak hour at 07:00 (16%). A secondary peak appeared in the afternoon around 18:00 (7%). The occurrence frequency was significantly lower during the night (19:00 to 06:00 the next day), likely due to the stable atmospheric stratification at night, which weakens the thermal and dynamic conditions conducive to dust lifting. Regarding the ending time of events, the dissipation frequency peaked in the morning from 07:00 to 09:00, with the highest concentration at 08:00 and 09:00. This pattern of occurrence and dissipation timing reflects the modulating influence of the diurnal cycle of local circulation and boundary-layer thermal forcing on dust activity.

4. Discussion

4.1. Influence of Meteorological Elements on Low Visibility

To investigate the key meteorological factors influencing dust-induced low visibility, we focused on analyzing the wind speed and direction characteristics at its onset. A wind rose diagram was plotted based on the filtered low-visibility samples (Figure 3). The results show that during low-visibility occurrences, the prevailing wind directions were primarily easterly winds (including ENE, E, and ESE), accounting for 49.5%, followed by northerly winds (18.3%) and westerly winds (10.4%). This suggests that strong winds from specific directions may be more prone to transporting dust from valleys or specific areas to the airport vicinity. The wind speed distribution indicates that low-visibility events are typically accompanied by higher wind speeds. The proportions for wind speed intervals of 3–6 m/s, 6–9 m/s, and 9–12 m/s all exceeded 22%, with the 6–9 m/s interval having the largest proportion (27.1%). Notably, even under conditions with wind speeds greater than 12 m/s, the event occurrence rate remained at 11.6%, while for wind speeds between 0 and 3 m/s, the proportion was 16.7%. This preliminarily indicates that higher wind speeds are a key dynamic condition for lifting and dispersing dust, leading to visibility degradation.

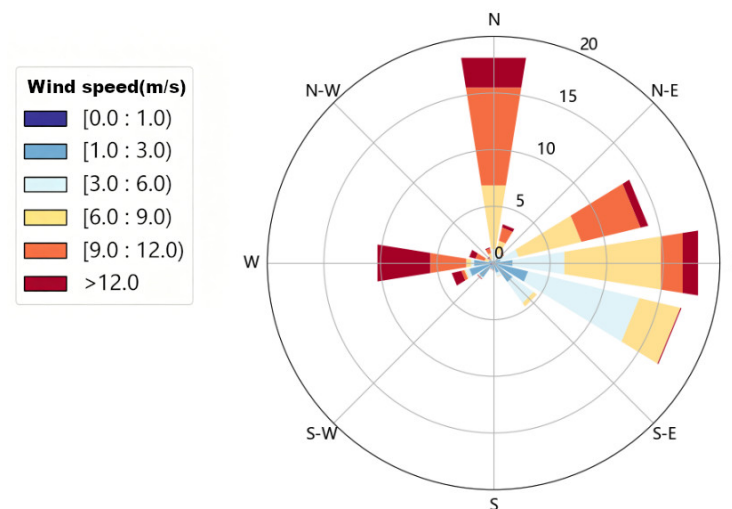


Figure 3. Wind rose diagram during the occurrence of dust-induced low visibility from January 2020 to July 2024.

We further analyzed the monthly variation characteristics of wind speed and direction (Figure 4). It should be noted that due to the extremely limited sample size from July to November, this analysis only covers data from December and January to June. The results show significant monthly differences in both wind speed and direction. During the winter months (December to February), the proportion of events with wind speeds ≥ 6 m/s was relatively low (December: 26.45%; January: 46.7%; February: 39.1%). This indicates that in the dry and cold season, even relatively lower wind speeds can trigger low visibility, likely because the surface dust material is looser and drier. Conversely, from spring to early summer (March to June), the proportion of events with wind speeds ≥ 6 m/s increased significantly (March: 70%; April–June: all $>86\%$), suggesting that stronger winds are required to effectively initiate dust events during this season. Seasonal characteristics in wind direction are also evident: winds were concentrated in easterly directions in December; the distribution was more scattered in January; concentrated in the east–north-east (ENE) direction in February; dominated by easterly and westerly winds in March; and mainly concentrated in northerly and easterly directions from April to June.

The relationship between relative humidity and visibility was analyzed using box plots (Figure 5). When visibility was lower (e.g., <2 km), the median relative humidity in January and March was below 20%, while in other months, the variation was smaller and relatively stable. Notably, when visibility was in the higher range (3–5 km), the median relative humidity for most months clustered around 40%. This non-monotonic relationship may indicate an optimal humidity range for sustained visibility reduction. Excessively low humidity facilitates dust lifting but also promotes rapid particle dispersion and dry deposition due to weakened inter-particle cohesion. Conversely, high humidity (e.g., $>60\%$) likely enhances particle hygroscopic growth, accelerating wet deposition processes [23]. In contrast, moderate humidity around 40% may provide conditions that favor the stable suspension of fine dust aerosols, thereby exerting a more prolonged influence on visibility. This hypothesized physical mechanism warrants further investigation through aerosol microphysical observations or numerical modeling.

Analysis of the relationship between temperature and visibility (Figure 6) shows that when visibility was poorer, the corresponding temperature tended to be higher, and vice versa, with this trend most apparent in February. For instance, data from February show that the median temperature was 6.2 °C when visibility was 1–2 km, 4.5 °C for 2–3 km, 0.5 °C for 3–4 km, and −1.4 °C for 4–5 km. This negative correlation may stem from

thermal effects: higher temperatures intensify surface thermal convection and alter pressure gradients, thereby enhancing vertical and horizontal airflow movements, increasing wind speed, and consequently, promoting dust lifting and long-distance transport.

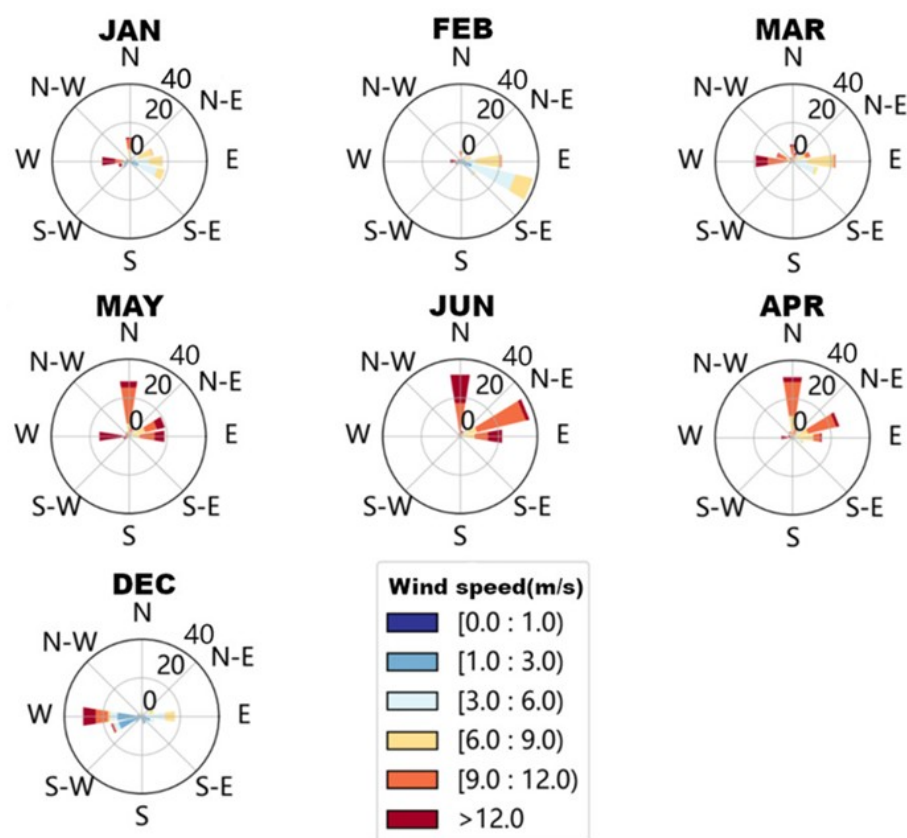


Figure 4. Monthly wind rose diagrams for dust-induced low-visibility processes from January 2020 to July 2024 (December and January–June).

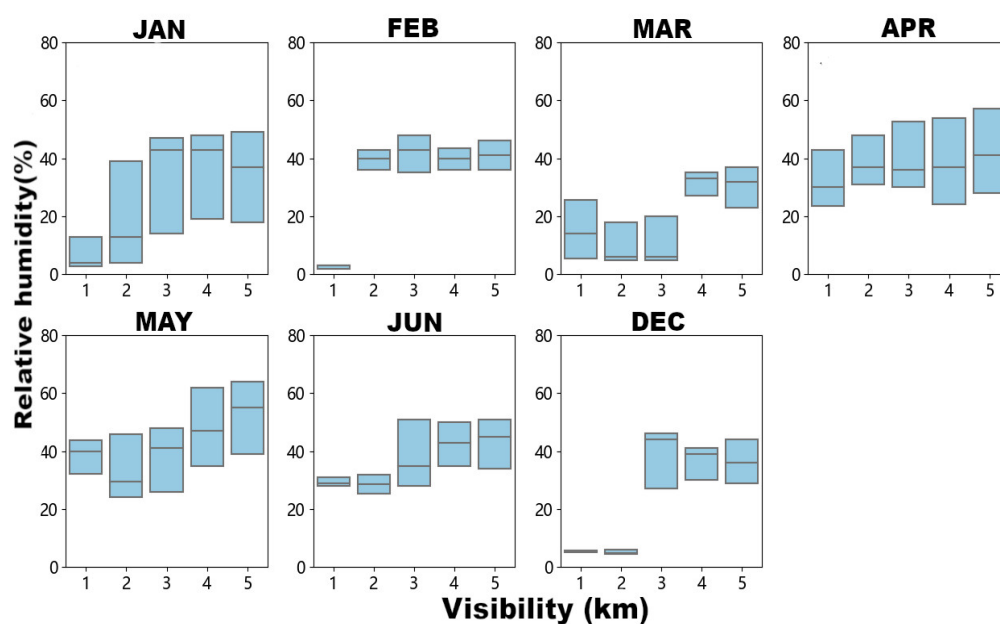


Figure 5. Box plots of relative humidity versus visibility during dust-induced low-visibility processes from January 2020 to July 2024.

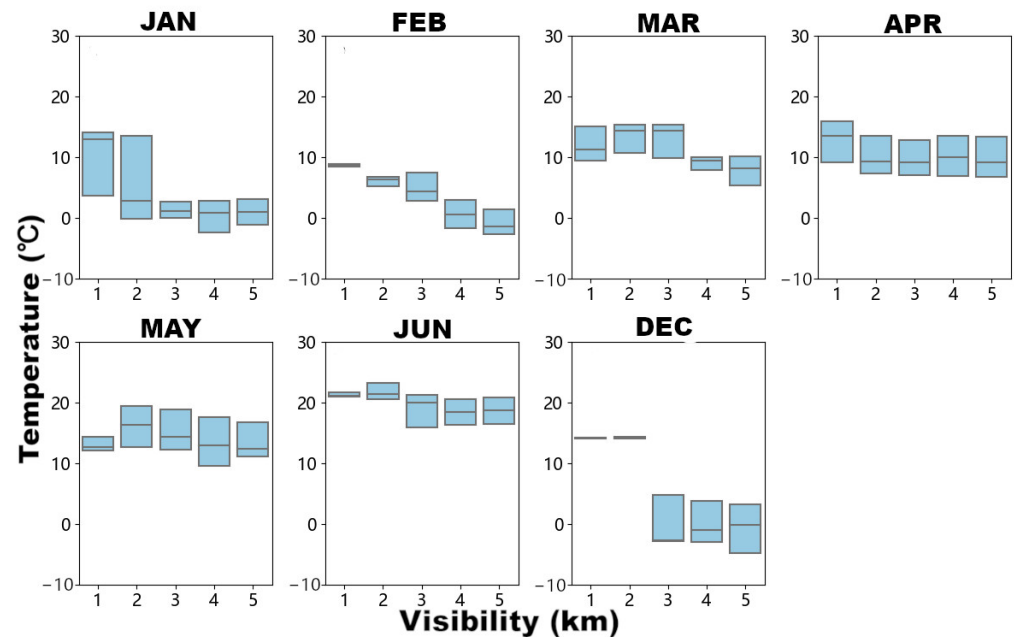


Figure 6. Box plots of temperature versus visibility during dust-induced low-visibility processes from January 2020 to July 2024.

Analysis of the relationship between atmospheric pressure and visibility (Figure 7) indicates that when visibility is in lower ranges (e.g., <1 km), pressure exhibits greater variability. For instance, in February, when visibility was between 1 and 2 km, the difference between the upper and lower quartiles reached 17 hPa. Conversely, when visibility is in higher ranges (e.g., 4–5 km), the pressure distribution is more concentrated and stable, with the median maintained between 1017 and 1021 hPa. This may suggest that low-visibility events often accompany more unstable or active pressure field conditions, while higher visibility corresponds to a relatively stable pressure environment.

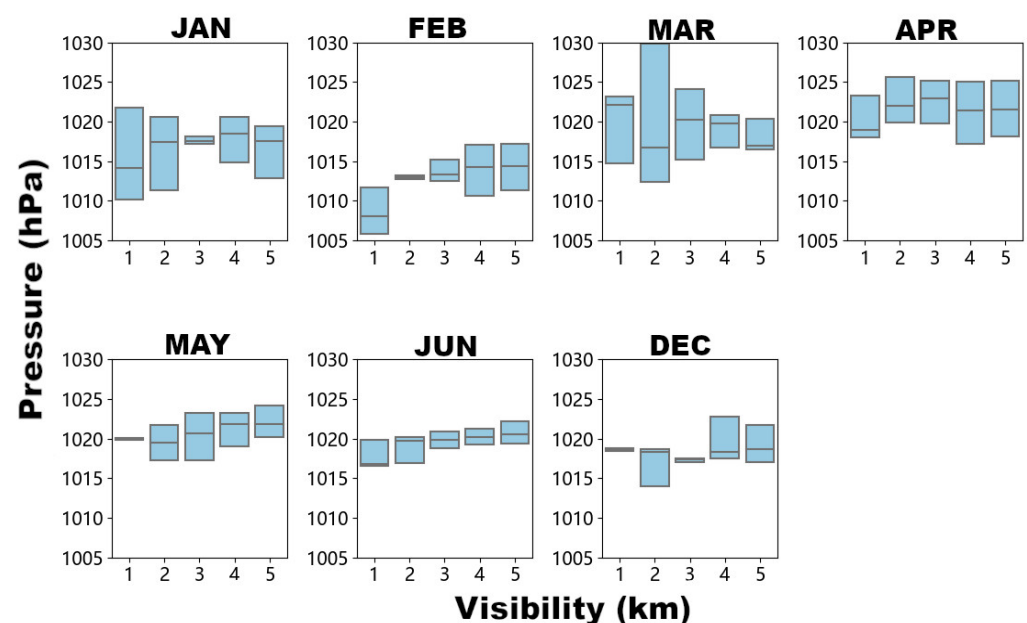


Figure 7. Box plots of pressure versus visibility during dust-induced low-visibility processes from January 2020 to July 2024.

The relationship between wind speed and visibility exhibited the most significant regularity across all months (Figure 8). A clear negative correlation demonstrates that visibility deterioration is consistently accompanied by an increased wind speed, whereas visibility improvement corresponds to a decreased wind speed. For instance, when visibility was below 1 km, the median wind speed exceeded 12 m/s in every month; when visibility was in the 4–5 km range, the median wind speed reached its minimum value. This trend is evident in all months, strongly indicating that wind speed is a decisive meteorological factor influencing dust-related visibility at Lhasa Airport. However, seasonal variations were observed: data from January show that low visibility could occur across a wide range of wind speeds, while from December to February, low visibility could still occur even when visibility was higher (3–5 km) and median wind speeds were low (<6 m/s), corroborating the conclusion that weaker winds can also trigger events in winter. For March to June, the trend of wind speed decreasing with increasing visibility was relatively gentle, suggesting that stronger winds are required in these months to effectively lift dust.

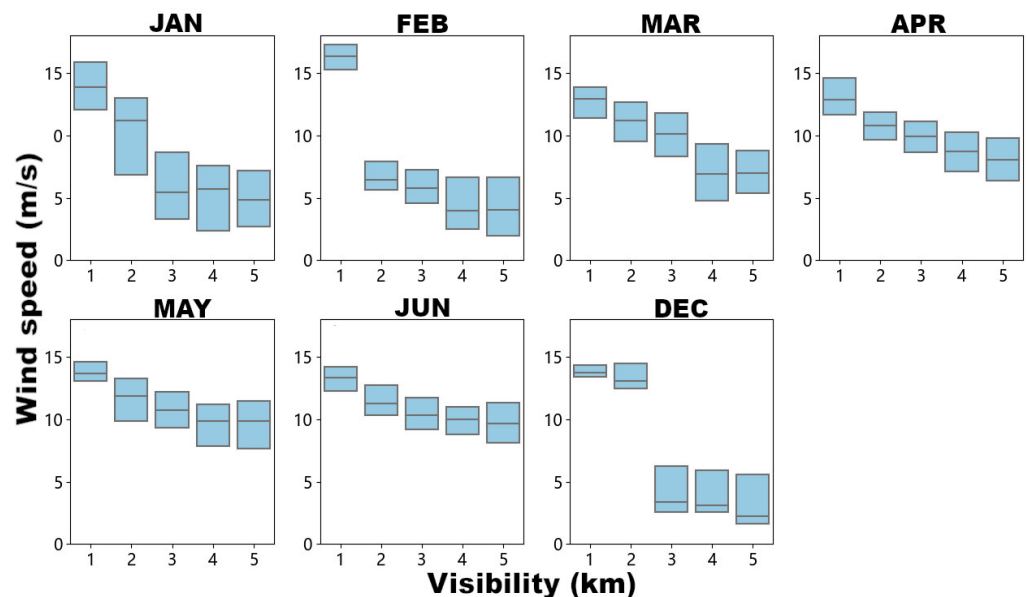


Figure 8. Box plots of wind speed versus visibility during dust-induced low-visibility processes from January 2020 to July 2024.

To quantify the relationships between various meteorological elements and visibility, scatter plots were drawn and linear regression analysis was performed (Figure 9). The results show that wind speed and visibility exhibited the most significant negative correlation (highest correlation coefficient), consistent with the valley wind effect typical of valley terrain and the physical mechanism of wind-driven dust lifting. A certain negative correlation trend exists between temperature and visibility, but the scatter distribution is more dispersed, suggesting a more complex relationship, likely influenced by multiple factors, such as solar radiation and underlying surface properties. The relationship between pressure and visibility was the most scattered, indicating that short-term pressure fluctuations have a weak direct impact on dust-related visibility at plateau airports. Relative humidity did not show a significant positive correlation with visibility, possibly related to the dry air and low water vapor content in plateau regions, which limits the hygroscopic growth effect of water vapor on dust particles.

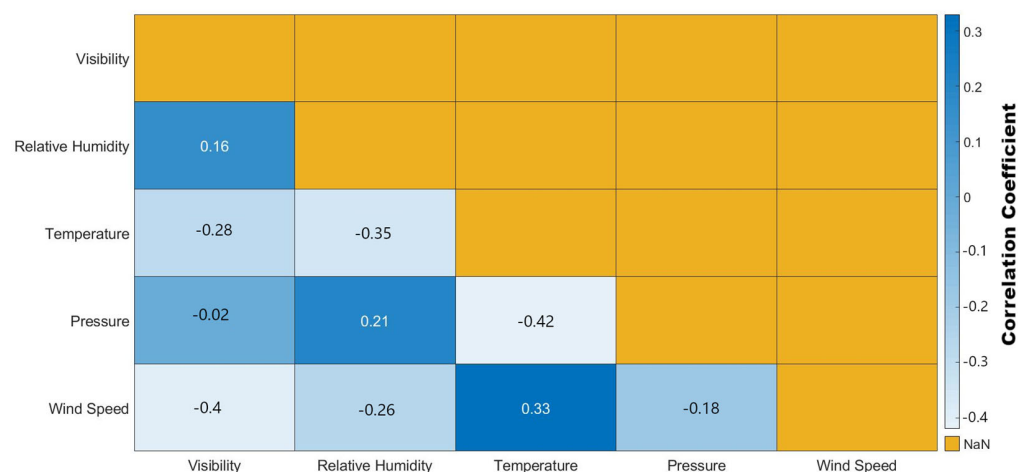


Figure 9. Pearson correlation coefficient matrix among visibility, relative humidity, temperature, pressure and wind speed during dust-induced low-visibility processes from January 2020 to July 2024.

4.2. Implications for Aviation Meteorological Services

Based on the above findings, this study provides actionable insights for enhancing operational meteorological support at Lhasa Airport and similar high-altitude valley airports:

4.2.1. Refined Forecasting and Early-Warning Indicators

Wind Direction as a Precursor: The persistence of northerly, easterly, or westerly winds, particularly easterlies, which may transport dust from upstream sections of the river valley, should be treated as a primary indicator for potential dust incursion and subsequent visibility degradation.

Quantitative Thresholds for Risk Assessment: The initiation of low-visibility risk warnings can be guided by specific meteorological thresholds. A critical combination involves surface wind speeds exceeding 6 m/s (with higher thresholds potentially applicable in spring and summer, e.g., ≥ 8 m/s) concurrent with relative humidity levels within the 30–50% range.

Temporal Focus for Enhanced Monitoring: Given the pronounced diurnal cycle, the period from 06:00 to 12:00 local time represents the highest-risk window for low-visibility onset. Meteorological services should prioritize intensified monitoring, nowcasting, and forecast consultation during these hours.

4.2.2. Decision Support for Aviation Operations

Strategic Planning: Airlines and airport authorities can leverage the clear seasonal pattern (peak frequency from January to April) for long-term strategic planning. This includes optimizing seasonal flight schedules, crew rostering, and scheduling maintenance activities to mitigate the impact of predictable low-visibility periods.

Tactical Response and Resource Allocation: When the key meteorological indicators described above are observed, and corroborated by wind lidar data showing sustained strengthening of low-level winds, Air Traffic Control and operational decision-makers can initiate advanced coordination. This proactive approach allows for more prepared responses to potential requirements for flow management, flight re-routing, or diversion decisions.

4.3. Analysis of Typical Low-Visibility Cases

Two typical dust-induced low-visibility processes were selected for a detailed analysis of their dynamic mechanisms using wind lidar data. Process on 5 December 2023: Low visibility occurred from 16:46 to 21:10, with a minimum visibility of 900 m. Wind lidar

data (Figure 10) show that before the low-visibility onset, the low-level wind field shifted from easterly to westerly and northwesterly winds. At the onset of low visibility, the low-level wind direction stabilized as northerly, with horizontal wind speed increasing to ≥ 10 m/s (maximum >15 m/s), while surface wind speed also increased to ≥ 7.5 m/s (short-term peak 10 m/s). The sharp drop in visibility coincided with the shift of low-level wind from northwest to north, and the stable northerly period corresponded to sustained visibility <5 km. Vertical wind speed generally increased at the onset of low visibility, dominated by upward motion (positive values), indicating active vertical mixing. Lidar echo intensity dramatically increased at the beginning of low visibility, with strong echo areas extending up to about 2 km altitude, and echo intensity increased from higher altitudes to the surface, possibly indicating higher dust concentration near the ground. Integrated analysis suggests that persistent strong low-level northerly winds (≥ 10 m/s), strong surface winds (≥ 7.5 m/s), and intense updrafts were the key dynamic conditions for this event.

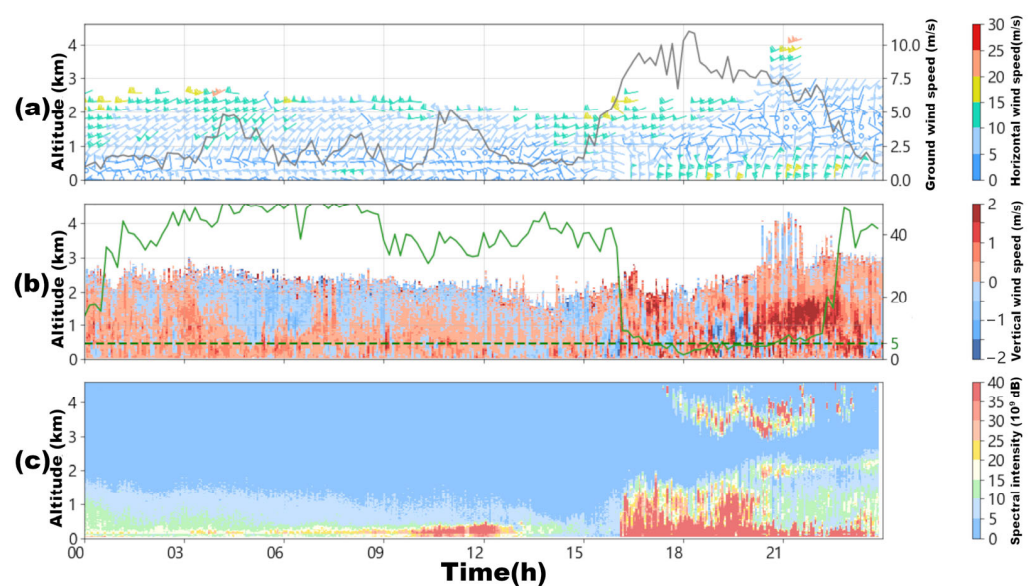


Figure 10. DBS mode data on December 5, 2023: (a) horizontal wind field and surface wind speed (gray line); (b) vertical wind field and visibility (green line); (c) spectral intensity color-filled plot.

Process on 1 February 2024: Low visibility occurred from 01:38 to 06:51, with a minimum visibility of 1500 m. Lidar data (Figure 11) show that before the onset, the near-surface wind direction was erratic and speed was low. At the onset, the near-surface wind direction stabilized as easterly, with speed increasing to ≥ 10 m/s, and surface wind speed increased to ≥ 7.5 m/s. After the process ended, the wind direction remained easterly but speed decreased, and visibility recovered. Vertical velocity showed a strong updraft area before onset; during the process, updrafts dominated below 1 km, while downdrafts dominated above. Lidar echo intensity showed a medium-intensity echo area before onset, suggesting that updrafts might have already lifted some dust; during the process, strong echo areas extended only to about 0.5 km, indicating a lower dust diffusion height. This case further confirms that stable, persistent low-level strong winds (≥ 10 m/s) and strong surface winds (≥ 7.5 m/s), coupled with intense updrafts, are the dynamic mechanisms for the prolonged maintenance of dust-induced low visibility. Moreover, the characteristic of lidar echo intensity increasing from higher altitudes to the surface appeared in both cases, which may generally indicate higher dust concentration near the ground than at higher altitudes during dust-induced low-visibility processes.

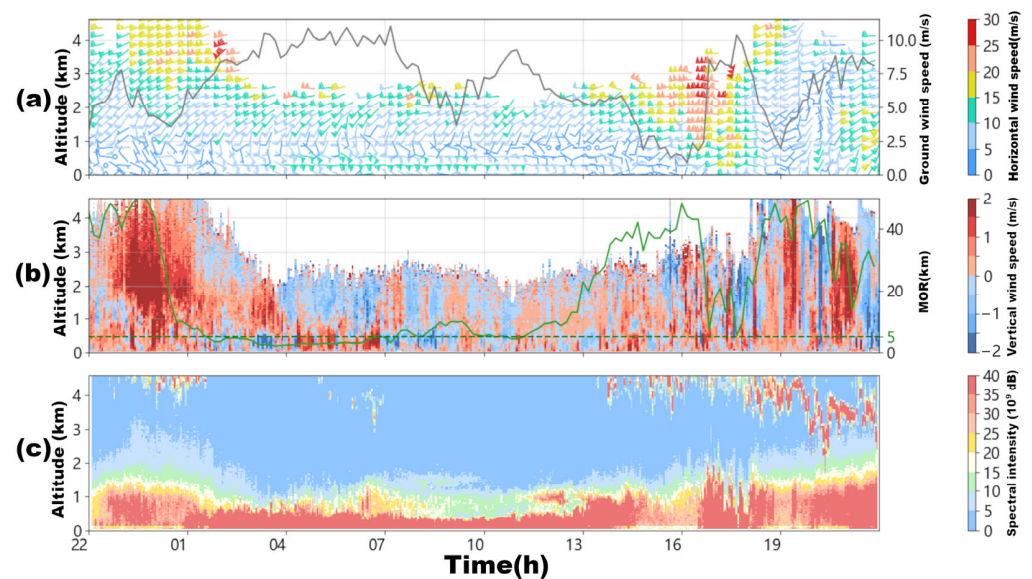


Figure 11. DBS mode data from 22:00 on 31 January to 22:00 on 1 February 2024: (a) horizontal wind field and surface wind speed (gray line); (b) vertical wind field and visibility (green line); (c) spectral intensity color-filled plot.

4.4. Applicability and Limitations of the Study

It is essential to acknowledge that the findings of this study are primarily derived from single-station data at Lhasa Airport, which is situated within the topographically complex Yarlung Zangbo River Valley. Consequently, the precise meteorological thresholds (e.g., specific wind speed and humidity values) and monthly distribution patterns identified here exhibit strong locality. Extrapolating these exact quantitative results to other airports should therefore be approached with considerable caution.

Nonetheless, several physical relationships elucidated in this study—such as the significant negative correlation between wind speed and visibility, the potential existence of an optimal humidity range for sustaining haze, and the short-duration nature coupled with pronounced diurnal variation in low-visibility events—may reflect common physical mechanisms through which dust weather impacts visibility in high-altitude valley environments. To disentangle generalizable patterns from site-specific characteristics, future research could apply the analytical framework established here to other airports on the Tibetan Plateau (e.g., Changdu Bangda, Ali Kunsha) or to high-altitude airports in analogous global settings for comparative validation. Similarities in key parameter relationships and thresholds would suggest the existence of transferable patterns, whereas significant discrepancies would underscore the critical necessity of conducting fine-scale investigations that account for local geographic and climatic particularities.

5. Conclusions

This study presents a comprehensive analysis of low-visibility weather at Lhasa Airport from 2020 to 2024. The key conclusions are as follows:

Dust weather (including blowing sand and floating dust) is the predominant cause of low visibility at Lhasa Airport, accounting for over 90% of low-visibility days.

Low-visibility events exhibit distinct seasonal and diurnal variations. The cumulative duration peaks in January and February, while such events are extremely rare from July to November. A clear bimodal diurnal pattern is observed, with the primary peak occurring in the morning (06:00–12:00 local time).

During dust events, visibility is most frequently (72.5%) observed in the 3–4 km range. These events are typically short-lived, with 75.5% lasting less than one hour.

Quantification of Key Drivers:

- The dominant wind directions associated with dust-induced low visibility are northerly, easterly, and westerly.
- The threshold wind speed for dust lifting shows seasonal dependence: under dry surface conditions in winter, relatively lower wind speeds (e.g., 4–6 m/s) can trigger low visibility, whereas stronger winds (typically ≥ 6 –8 m/s) are required in spring and summer.
- Moderate relative humidity around 40% appears most conducive to sustaining reduced visibility within the 3–5 km range.
- Case studies utilizing wind lidar data confirm that persistent strong low-level winds (≥ 10 m/s), coupled with high surface wind speeds (≥ 7.5 m/s) and intense upward motion, are critical dynamic conditions for the initiation and maintenance of dust-related low-visibility processes.
- Practical Implications:
 - For Meteorological Forecasting: Forecasters should prioritize specific wind directions, seasonally dependent wind speed thresholds, and the morning high-risk period as core indicators for early warnings.
 - For Airport Operations and Air Traffic Management: Understanding the monthly variation patterns of low visibility facilitates proactive adjustments to flight schedules and resource allocation. Recognizing the short-duration nature of these events can help optimize real-time traffic management decisions, minimizing prolonged operational disruptions.

The findings highlight the critical importance of integrating high-resolution local observations—including remote sensing data such as wind lidar—and applying quantitative thresholds to improve the accuracy of nowcasting and operational decision-making for low-visibility weather at Lhasa Airport. Furthermore, the analytical framework established in this study provides a transferable paradigm for investigating similar weather phenomena at other high-altitude valley airports.

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